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ON THE EARTH-MOON ROUTE -- A BIOLOGICAL EVALUATION OF RADIATION IN SPACE FLIGHTS

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Four years ago, 12 April 1961, Soviet cosmonaut Yuriy A. Gagarin made his flight and became the first resident of the Earth to go beyond its boundaries. This began the grand era of Man's subjugation of space. Nine Soviet cosmonauts have travelled this trail around the Earth. Cosmonauts' day 1965 sees new, outstanding achievments. Over 60 satellites in the Cosmos series have been launched. The "Zond-2" interplanetary probe is investigating conditions in the Earth-Mars sector. Equipment for tracking and communicating with space ships has been improved. But scientists are already thinking about the next daring step into space. Apparently, the Moon will be the first heavenly body visited by Man. It is therefore natural that the investigation and biological evaluation of the physical and, especially, radiation conditions with which Man will have to cope during his flight to the moon is a matter of great scientific and practical interest.

The radiation situation in near-Earth space is the subject of a good deal of available data, particularly the various parameters and properties of some of the physical factors there, which allows a certain degree of evaluation of the danger and the capabilities of man in near-Earth flight. We have in mind primarily the study of the composition, energy spectrum, spatial and temporal distributions of cosmic radiation, investigation of the biological effectiveness of various types of ionizing radiation.

Some successes have been attained in the area of studying the influence of weightlessness on the human organism as well. The flight of V. F. Bykovskiy, like the flights of the other cosmonauts, gives us reason to hope than Man will probably be able to sustain weightlessness for over five days without losing his working ability.

There is considerable interest in some of the literature data on technical means for realization of the idea of a manned flight to the moon. It is perfectly clear, however, that the problem of technical and bio-medical provisioning for such a flight is still far from fully resolved, and the proposed dates for the flight sometimes seen in American literature -- 1967-1970 -- must be looked upon as very rough approximations. Flight time will doubtless depend to a great extent on the results of further investigation of the physical conditions in interplanetary space, the results of investigations of the Moon itself and the solution of a number of bio-medical problems concerned with flight safety.

This article contains an attempt to analyse the radiation situation in near-Earth space and evaluate the danger present from ionizing radiation which would be encountered by a pilot on a flight along the Earth-Moon path.

Before the discovery of the Earth's radiation belts, ionizing radiation in space was not considered to be a factor which might have an essential influence on flight safety. However, since the discovery of the zones of radiation, especially that radiation which accompanies chromospheric flares on the Sun, cosmic radiation has been seen to be one of the major barriers in the path of Man's penetration of space.

As is known, cosmic radiation includes galactic rays (primary cosmic radiation), the ionizing radiation of the Van Allen radiation belts and the radiation from the Sun, which is considerably increased during chromospheric flares (see *Priroda*, No 1, 65, pp 23-32). The artificial radiation belts formed as a result of atomic weapons tests in space occupy a special place.

In order to evaluate these types of cosmic radiation from the point of view of their radiation danger, let us briefly review the composition of each type of radiation, its energetic spectrum, interactions of charged particles with matter and the biological dosage resulting from each radiation type.

Primary Cosmic Rays

These rays consist of a stream of charged particles, mainly protons, which falls practically isotropically from space. At the present

time it is accepted that the stream of primary cosmic rays consists of approximately 85% protons, 13-14% α-particles and 1-2% particles with charge $Z \geq 3$. It is considered that all these primary particles are completely free of orbital electrons, i.e. that they are the nuclei of various elements. The relative distribution of these nuclei in the rays is similar to the cosmic distribution of the corresponding elements, though there is a slight excess in the heavy nuclei, especially at great distances from the Earth. The energy of the particles in the primary cosmic rays varies widely, from 20-40 up to 10^{12} *Mev/nucleon*.

In spite of a great number of experiments on the determination of the charge spectrum of these primary particles, at the present time the exact form of this spectrum is still not known. This is due to the low intensity and difficulty of identification of heavy Helium nuclei. According to the data obtained from Soviet Satellite studies, the intensity of the primary rays varies in interplanetary space with the 11-year solar cycle from 2 (maximum of solar activity) to 4.5 *particles/cm² sec*.

Let us attempt to determine the dosage of primary cosmic rays which would be received by a cosmonaut located beyond the magnetic field of the Earth. Calculated data on the daily dosage of the various groups of particles resulting from primary cosmic rays in free space are presented in table 1.

Table 1

Particles or Nuclear Group	Stream of Particles/cm sec	Daily Dosage, Millirads	Daily Dosage, Millirem
Protons	1.8	4.9	5.0
α-Particles	0.4	5.5	5.5
L(3<Z<5)	$1 \cdot 10^{-2}$	0.4	0.5
M(6<Z<10)	$2 \cdot 10^{-2}$	5.5	33.0
H(z<10)	$1 \cdot 10^{-2}$	5.2	96.0
Total:	2.24	21.5	140.0

Considering the results of investigations performed on cosmic rockets, the intensity of primary cosmic rays which we used in our calculations was 2.24 *particles/cm² sec*. The coefficient of relative biological effectiveness (RBE) for the various particles was determined on the basis of the data from graphic plots of the dependence of RBE on the linear loss of energy (LLE).

If we consider that the composition of the primary cosmic rays is practically constant, the daily dosage will vary, depending on the level

of solar activity, from 125 to 270 mrem. A protective cover around the spaceship with a thickness of 1-2 g/cm^2 will not change this value essentially.

It should be pointed out that electrons have been discovered in cosmic rays in quantities of about 1%, as well as an insignificant number of γ-rays, which add no significant amount of ionization. In analysing the question of the radiation danger from primary cosmic rays, the ionization caused by the electrons and γ-rays can be ignored.

As a result of the screening action of the Earth and its magnetic field, the summary dosage of primary cosmic rays in the orbits in which the Soviet and American cosmonauts have flown is little more than 1/2 the dosage in free space. Table 2 shows the disages received by Soviet cosmonauts in the Vostok ships.

Table 2

Cosmonauts	Duration hrs	Dosimeter Types A mrad	A mr/dy	B mrad	B mr/dy	C mrad	C mr/dy
Gagarin	1.5	0,5	8,4				
Titov	25	13±2	12±2				
Nikolayev	94	64±1	16±1	58±7	15±2	43±1	11±1
Popovich	71	48±1	16±1	51±7	17±2	32±1	11±1
Bykovskiy	119	75±2	15±1	81±6	16±1	50±1	10±1
Tereshkova	71	48±1	16±1	42±2	14±1	30±1	10±1

It can be seen from the table that the average daily dosage received in the experiments corresponds with the calculated dosage, within the margin of measurement error. From 85 to 90 percent of the integral dosage received in these flights was in the form of primary cosmic rays, mainly the heavier components.

Experiments performed on recovered satellites and the Vostok class ships have allowed a rather complete evaluation of the dosage of cosmic radiation to be received at altitudes of 180-320 km. Various biological subjects have been used for this, varying in organization level from bacteria and microspores to dogs, with the application of various special methods of investigation.

Analysis of the results produced has shown that some changes, primarily in the genetic apparatus, are produced in lysogenic bacteria, some plant subjects and fruit flies by the action of cosmic radiation.

For example, in the flight of the "Vostok-5" of almost 5 days, the summary dosage of radiation was recorded as approximately 80 mrad (physico-chemical dosimeters) and 50 mrad (gas-discharge counter). If we take the RBE for the heavy components of the primary rays as 10, the dosage in rem in this case will be about 450-750 mrem. This sort of summary dosage could be determined only by very sensitive objects to radiation, with the application of the proper tests. By this, we can understand the changes registered, for example, in the lysogenic bacteria and the lack of radiobiological effects in other organisms less sensitive to radiation.

When Man flies through free cosmic space, the integral dosage is doubled in relation to the primary cosmic rays and, for example, would reach 1.8 to 4 rem in 5 days. An evaluation of this dosage leads to the conclusion that it does not exceed the limits set for cosmonauts and could hardly result in a change in the state of health of a pilot. However, we should be aware of the biophysical peculiarities of the action of heaby particles, connected in the main with the capacity of these particles to cause very high ionization densities in a short flight path (the "strike" phenomenon) or nuclear transformations (the "star"seen on fig. 1). In consequence of this, it has been suggested that the incidence of heavy nuclei in the hypothalmic portion of the brain, cornea, retina, etc. might cause destruction in a large group of cells and, consequently, lead to disruption of, for example, thermo-regulation, cause cataracts, microstomes, etc. (fig. 2 and 3).

The "strike" phenomenon is a new type of radiobiological activity, the study of which has just been begun. Up to now, more or less surprising data have been produced on the action of the heavy component both in flight and in the laboratory in experiments on small biological subjects or individual cells, but there is a complete lack of experimental data on the possible effects of local damage in some organs and centers on the organism as a whole. On the basis of some theoretical calculations and biological experiments performed in Soviet and American ships, it can be assumed that the probability of such local destruction of individual groups of cells, if it exists, is slight and will have no practical significance for flights of several weeks duration.

Ionizing Radiation of the Van Allen Belts

The presence of three radiation belts around the Earth has been experimentally proven -- the inner, the outer, and the "outermost" belts.

The radiation of the inner belt consists of protons and electrons. The intensity maximum, according to various sets of data, is for protons from $2 \cdot 10^4$ to 10^5 particles/cm^2 sec and for electrons with energies of over 40 Kev -- 10^9 particles/cm^2 sec. The thickness of the

high energy radiation belt is approximately 4-5 thousand km. After breaking away from the surface of the Earth, a spaceship would be located in this belt for about 15 minutes. The average dosage caused by protons in a ship with a protective cover of 1 g/cm^2 in an orbital section passing through this belt would be approximately 5 rem/hr. The electrons of the outer radiation belt would be fully absorbed by the shield, and the disage due to the brehmstrallung which would appear would be about 0.1 rad/hr.

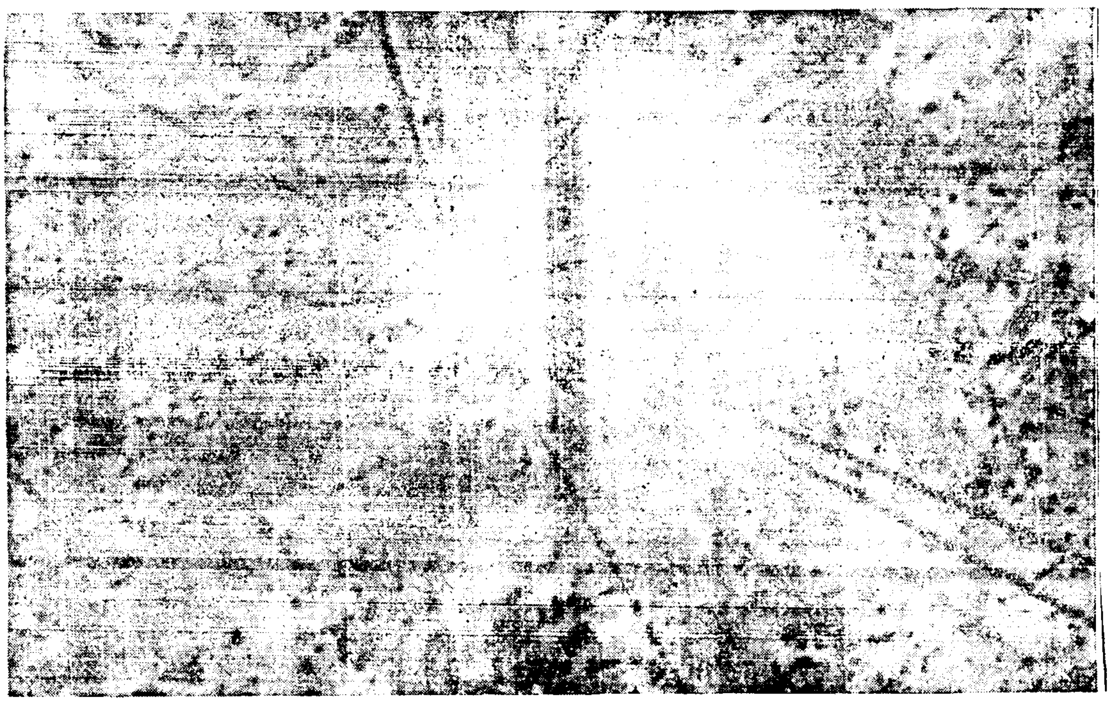

Figure 1

"Star" formed as a result of the collision of a particle in a primary cosmic ray with an atom

The radiation of the outer belt consists mainly of electrons with energies from 20 Kev to several Mev. The intensity of electrons in the center of the belt with energies over 40 Kev is 10^8 particles/cm^2 sec. The radiation of this belt makes no essential contribution of the summary dose, though the time the ship spends in the outer belt is about 2 hours. This contribution, with a protective layer of 1 g/cm^2, will be equal to 0.2-0.3 rad, due to brehmstrahlung.

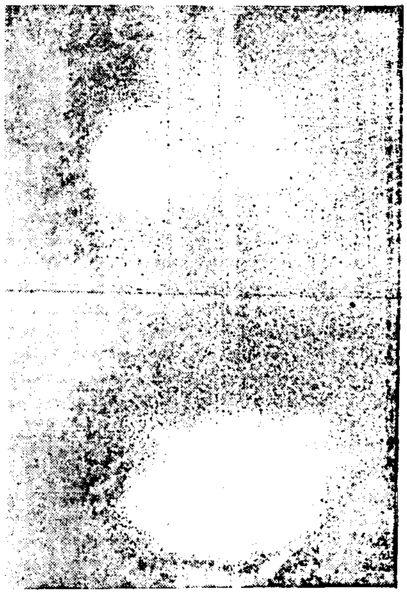

Figure 2

Normal late anaphase in cells of mouse bone marrow

The electrons of the "outermost" belt, with slight energies, are fully eliminated by the protective shield we have described, and make no contribution to the integral dosage.

Thus, a cosmonaut on board a spaceship with a protective layer of 1 g/cm^2 would receive a summary dosage of 2.5-3.5 rem during passage through the radiation belts on passage to the Moon. This dosage, like the primary cosmic ray dosage, presents no threat to the health of the cosmonaut.

In the artificial belt, the intensity of the radiation, the spatial distribution of the radiation and the life of the particles injected depend on a great number of factors and cannot at present be theoretically calculated. Predictions made on the basis of individual experimental factors in many cases have been proven wrong.

Measurement of the dosage in the center of the artificial belt formed as a result of the nuclear explosion detonated by the USA over

Johnston island 9 July 1962 has shown that high radiation levels exist in this belt. Thus, the dosage of radiation behind a protective layer 4-5 g/cm^2 in thickness two months after the explosion was 3 rad/hr. With a protective layer of 0.4 g/cm^2, the dosage two months after the explosion was 2000 rad/hr.

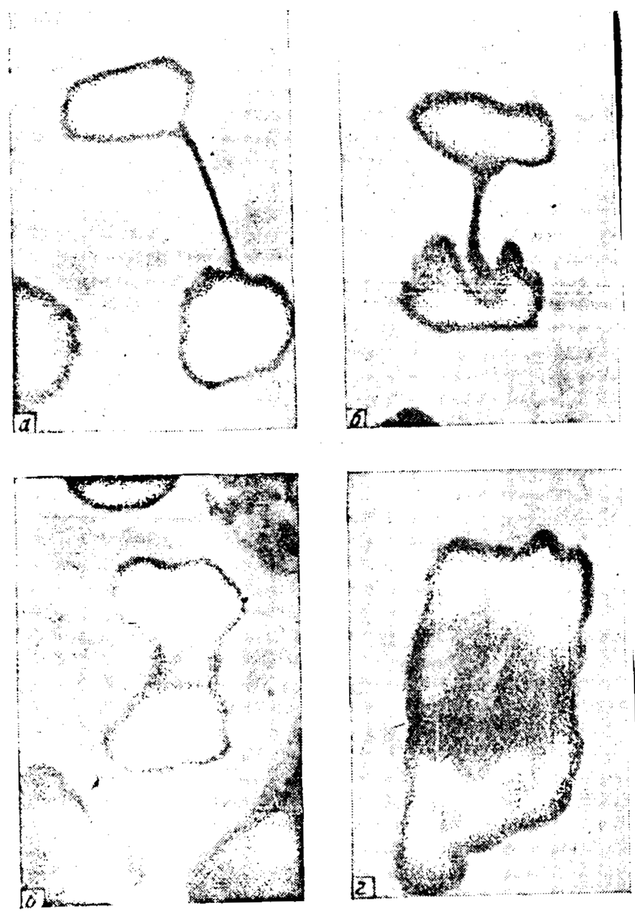

Figure 3

Types of chromosome disruptions caused in the same cell type as shown on fig. 2 after a flight. The same disruptions can be caused by vibration alone. Chromosome bridges (top); adherance of chromosomes and formation of false bridges (bottom)

Thus, the nuclear explosion of 9 July 1962 formed a rather extensive zone in which electrons are of approximately the same danger as the protons of the inner belt. It is difficult to predict the future dynamics of the artificial belt, so that the radiation danger for a concrete flight can be determined only by direct measurement of the radiation levels in the given area. If a flight were to take place in the trajectory for a flight around the Moon and conditions were as described above, the cosmonaut would receive a dosage of 2-3 rem behind a barrier of 1-2 g/cm^2 in the course of his passage through the artificial belt.

Radiation from Chromospheric Flares on the Sun

This radiation is made up of approximately 90% protons and 10% α-particles. With some flares, heavy nuclear particles with Z up to 18 have been found.

Flares of solar protons can be divided according to intensity and energy spectrum into three groups: high, middle and low energy.

High energy flares are those which produce secondary radiation observable at sea level. Proton energies may be as high as 20 Bev, flare durations up to several tens of hours, with relatively low flare intensity. Such flares include those of 28 Feb and 7 March 1942, 25 July 1946, 19 Nov 1949 and 23 Feb 1956. The last one was the greatest. It is characteristic that all these flares took place under conditions of declining or increasing solar activity. On the average, they occur every 4-5 years.

An example of a middle energy flare could be the 10 July 1959 flare, or any of those occuring on 16 July 1959, 12 Nov 1960, etc. The energy of the protons radiated reaches a few Bev. Such flares occur about 2 to 4 times per year during high solar activity periods.

The third group includes the flares of 22 Aug 1958, 10 May and 14 Sept 1959, whose proton energies did not exceed a few hundred Mev. Such flares occur 10-12 times per year.

Solar flares are divided into seven classes by optical brightness (1, 1^+, 2, 2^+, 3, 3^+, 4). The generation and radiation of dangerous protons usually is a characteristic of flares of classes 3 and 3^+.

In order to determine the degree of radiation danger of solar flare protons and design protection from them, we must know the flow and energy spectrum for the entire duration of the flare, especially during the maximal intensity phase, since the main portion of the dosage occurs in this

period. It is also necessary to know the direction of movement of the main mass of the charged particles.

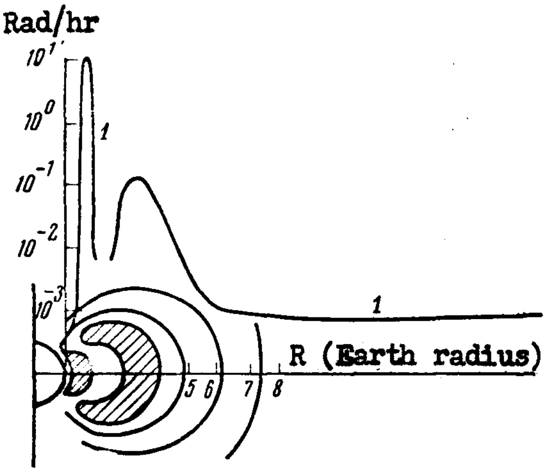

Figure 4

Schematic graph (1) of change in radiation level behind 2-3 g/cm^2 shield with increasing distance from the Earth along the geomagnetic equator

Various authors have presented calculations of the dosages, determined the required shielding from proton radiation of solar flares of all classes. The calculated dosage values and, consequently, recommendations for physical shielding vary widely, depending on the initial data accepted for the calculations, flight conditions, etc. However, all the calculations, no matter how they are produced, show clearly the great danger from solar flare protons, especially when the flight path goes beyond the magnetic field of the Earth (fig. 5).

Thus, for example, in order that the integral dosage not exceed 100 rem, a protective shield of 13 g/cm^2 must be used against a solar flare of the class of the February, 1956 flare, 15 g/cm^2 of shielding would be needed to afford the same protection from a flare of the magnitude of the May, 1959 flare, and only 2 g/cm^2 for the flare of August, 1958. Reduction of the radiation dosage to the maximum permissable

level -- 25 rem -- would require shielding under the same conditions of 32, 25 and 2.8 g/cm^2 respectively. It is completely obvious that fulfillment of these requirements would involve great, for the time being unsolvable, difficulties.

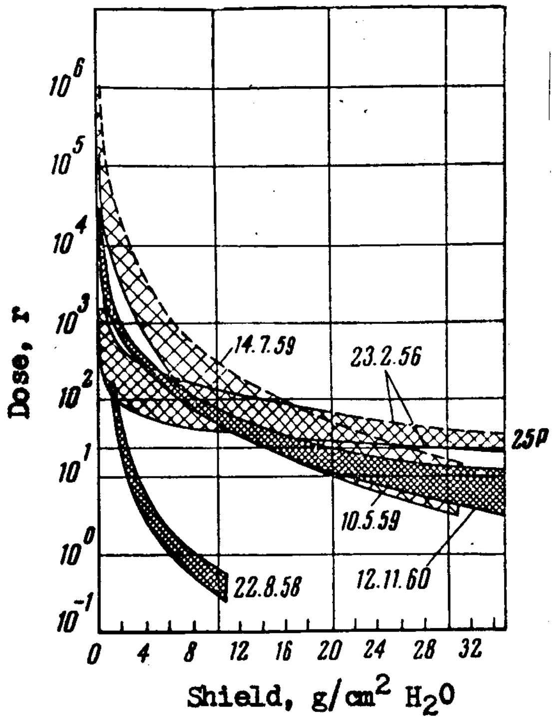

Figure 5

Approximate evaluation of dosage limits in the center of a spherical water shield for various solar flares, according to the data of the American investigator T. Folsh [name transliterated from Russian]. Dates of flares shown on figure

The Radiobiological Effect

Thus, a cosmonaut in interplanetary space, shielded by approximately 3 g/cm^2 of shielding, could receive a dosage from several tenths to several hundred rads from a solar flare. Naturally, the question arises of the possibility of evaluating the biological effect of these dosages. It is

known that one-time irradiation under Earth conditions with a dosage of about 25 rem causes definite changes in an organism, for example in the nervous and circulatory systems, and that a dosage of 100 rem results in an initial reaction of nausea, increased fatigue and other symptoms of sickness; the capacity for work is reduced. After one-time exposure to 200 rem, in 50% of the cases the typical symptoms of acute radiation sickness arise, with nausea, vomiting, dizziness, loss of strength. Death occurs, as a rule, with a dosage of around 300 rem, but can take place with lesser dosages as well.

Flight conditions, apparently, change the reaction of an organism to the action of ionizing radiation. However, evaluation of the ways in which the changes are manifested during and at the outset of radiation damage is at present difficult.

The radiobiological effect depends on many factors: the amount of the absorbed, integral dosage, the type of radiation (ionization density), the duration of radiation (radiation power), the manner in which the organism is irradiated -- fully or partially, as well as on the functional state of the organism, its resistance to radiation.

In the case of irradiation by solar protons during flares, two facts will probably lower the effect of the radiation -- the relatively long duration of the radiation (low radiation power) and the presence of various shields aboard the spaceship which will prevent total irradiation. At the same time, some of the conditions of flight -- emotional tension, changing regime, reduction in physical activity, change of gas composition, etc. -- reduce the resistance of the organism, increasing the effect of the radiation.

There is great confusion in relation to the effect of weightlessness on the reaction to radiation. The first experiments on this subject indicate that the effect of cosmic radiation is additive under conditions of extended weightlessness.

In evaluating the initiation and flow of radiation damage, we must keep in mind not only the factors in force during the flight, but also the factors acting upon the organism during the return of the spaceship. These include, first of all, overloads on the cardio-vascular system, the resistance to which is considerably reduced under the influence of ionizing radiation.

The relative biological effectiveness RBE of solar protons can be determined at present only indirectly, on the basis of calculated data and the results of laboratory experiments performed with various accelerated protons.

Analysis of experimental results produced by a number of authors leads to the conclusion that the RBE coefficient for protons of solar

flares, keeping in mind the radiation spectrum as a whole, must be higher than 1 (about 1.5). It must also be kept in mind in evaluating the integral dosage received by the cosmonaut that a considerable portion of this dosage will come from secondary neutrons, whose RBE coefficient is no less than two.

To sum up the above, it can be considered that under flight conditions the radiation damage will be complicated by a number of flight factors. This must be considered in determining permissable dosages of radiation for cosmonauts and in designing shield material and measures. It is fully obvious that one of the main sources of irradiation of the cosmonaut beyond the magnetic field of the Earth will be solar flare protons.

What is the probability that the ship will encounter a dangerous flare and that the cosmonaut will be exposed to over-radiation in a flight around the Moon? This depends on the mean probability of appearance of a flare and the duration of the flight. For a flight of one week, this probability is rather high; 16% for flares of the 22 Aug 1958 type, 5.8% for flares of the 10 May 1959 type and 0.3% for flares of the 23 Feb 1958 type, in periods of increased solar activity. This danger increases with increasing flight time.

We have briefly analysed the physical characteristics of the main types of cosmic radiation and determined the biological dosages (basically their upper limits) caused by each type of radiation. According to our data, the integral dosage of radiation from primary cosmic rays, the radiation of the natural and artificial radiation belts behind a shield of 1-2 g/cm^2 should not exceed 10 rem for a two-week flight around the Moon. Consequently, a 1-2 g/cm^2 shield would insure safety from radiation for the crew, if the flight takes place during a solar quiet period.

The real threat to the health and life of the cosmonaut is presented by solar flare protons. In this case, in order to increase the radiation safety, it would be expedient to increase the physical shielding to 3 g/cm^2, which would allow a reduction in the integral dosage during a flare such as that of 22 August 1958 to the permissible level of 25 rem. The problem of physical protection from the protons generated in a flare of the type which took place 10 July 1959 or 23 Feb 1956 is technically not solvable at the present time.

How could the danger of proton radiation with this type of flare be reduced? First of all, by prediction of such flares. Existing methods of prediction allow 75% accuracy in the prediction of flares 2-3 days in advance. This is not much time, so the problem of flare prediction must be intensively studied, in order to develop prediction apparatus for installation both on the ground and in spaceships.

Secondly, the resistance of the organism to the action of protons can be increased essentially by various medicinal preparates. Successful

experiments along this line have given us reason to hope that medicinal protection for cosmonauts from ionizing radiation may be one of the main links in the system of measures for radiation safety of cosmic flights.

* * *

In conclusion it should be noted that the progress in the investigation of space by man, especially the brilliant flight of the cosmic ship "Voskhod" and V. M. Komarov, K. P. Feoktistov and B. B. Yegorov will yield new information on the physical parameters and properties of cosmic space, necessary for creation of the conditions which will allow flight safety. The biological indication of the new paths for these flights has, therefore, even greater significance for further mastery of cosmic space.